# Safety Control of Teleoperation System under Time Varying Communication Delay

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Abstract— This paper describes the safe control method on bilateral control system. The control stability in bilateral control under time variance communication delay does not always stand for operation safety. Local controller is needed to secure the safety when communication delay becomes large. A novel method to change over the local controller and global bilateral controller due to communication delay is suggested. At the same time, the stability of global bilateral control is also assured with the conventional stability assurance method. Experimental system that joints manipulators in Slovenia and Japan is constructed. The validity of the suggested method is shown with this experimental system.

## I. Introduction

Internet was expanded across the world and its connection band was broaden. Ever since, the significance and role of information in daily life have been changed greatly. Digital information is applied for various uses. Music and movies are able to be delivered immediately. Remote education, remote security system, video conference and so on are advancing convenience. Many kinds of new businesses are forged at this very moment in the field of e-business. Progress in internet technology is now changing the scheme of communication in human life and producing many new types of communication tool.

Bilateral control system also has possibility to be one of these examples. Many studies about bilateral control have been done in order to reproduce the haptic sense in distant place [1], [2]. Applying these methods to internet system, bilateral control system could be applied as a communication tool to transmit the haptic sense.

In internet communication, time variance communication delay occurs. This communication delay degrade the reproducibility of haptic sense. Furthermore, it may make the control system unstable. Therefore, many studies have been focused on the issue of stability assurance under communication delay [3], [4], [5], [6], [7]. Anderson and Spong [3] proposed a bilateral control method based on the passivity concept and the scattering theory to achieve the control stability under communication delay. Niemeyer and Slotine [4] suggested the notions of wave variable and wave transmission. They utilized these notions to teleoperation system design. Based on these notions, Yokokohji et al. [5] suggested a method to assure the control stability under time varying communication delay. Oboe [7] studied on Internet-based force-feedback telerobotics equipment and showed that it is important to constantly monitor communication's characteristics.

As mentioned above, there are a lot of studies that assure the control stability of bilateral control under communication delay. However, the control stability and the safety of operation is not always equivalent. In this paper, a method to secure the safety of bilateral control teleoperation is suggested. It is shown that there are some unsafe situations even if the bilateral control system is perfectly stable. Control system with local force controller is designed so that the local force controller secures the safety under communication delay. Variable control gain $K_c$ is introduced so that the extent of local force feedback can be changed according to the communication delay. The method of Yokokohji [5] is applied in order to assure the stability even if variable control gain is applied.

A bilateral teleoperation system that joints manipulators in Slovenia and Japan is constructed in order to examine this method. This system is appropriate to prove the validity of control method under unreliable communication.

This paper is organized as follows. In section II, the construction of experimental system is shown. Conventional stability assurance method is explained in section III. A new control architecture that considers safety is suggested in section IV. Section V concludes this study.

## II. Construction of experimental system

In order to examine the validity of bilateral control method, we established a bilateral teleoperation system that joints manipulators in Slovenia and Japan. Its brief over view is shown in Fig. 1

1 DOF manipulators are put on both sides, Slovenia and Japan. Respective manipulators give the position and velocity output to the computer on respective sides. On the contrary, computers give the reference value to drivers and drivers give current inputs to the motor. Although external force information is needed for this method, force sensors are not used in this system.

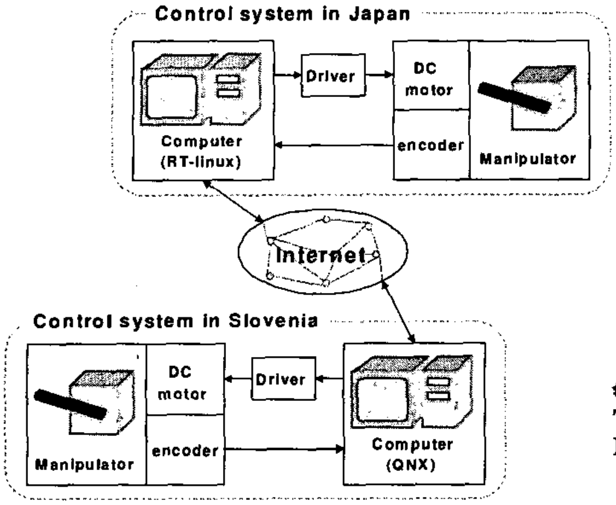

Fig. 1. Brief overview of the bilateral teleoperation system

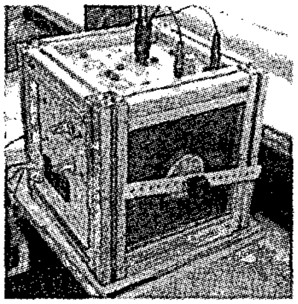

Fig. 2. Manipulator in Slovenia

External force observer [10] is applied to estimate the external force without any sensors.

Fig. 2 shows the manipulator overview in Slovenia side. Table I shows the manipulator parameters in Slovenia side.

TABLE I

Manipulator parameters on Slovenia side

| | |
|---|---|
| Rated power output$[W]$ | 30 |
| Rated motor torque$[mNm]$ | 73.7 |
| Reduction ratio | 19/173 |
| Number of encoder pulse$[P/R]$ | 500 |
| MOI at reducer output shaft$[kgm^2]$ | 0.000185 |

Fig. 3 shows the manipulator overview in Japan side. Table II shows the manipulator parameters in Japan side. There are two identical manipulators in Japan side. Therefore, it is also able to examine bilateral control system with these two manipulators by giving the virtual time delay. When we need to examine the control system in arbitrary time delay, we examine with these two manipulators and realize the virtual time delay by program. However, it is important to test the control method thorough the experiment between Slovenia and Japan. The result proves the validity of the control system under actual communication delay. The distance between Slovenia and Japan is about 9000 km.

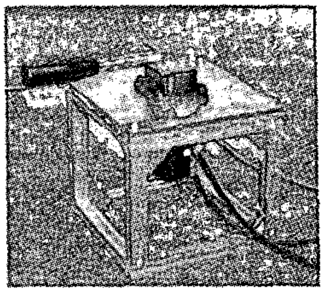

Fig. 3. Manipulator in Japan

TABLE II

Manipulator parameters on Japan side

| | |
|---|---|
| Rated power output$[W]$ | 50 |
| Rated motor torque$[mNm]$ | 159.0 |
| Reduction ratio | 1/33 |
| Number of encoder pulse$[P/R]$ | 2048 |
| MOI at reducer output shaft$[kgm^2]$ | 0.00535 |

Both computers are connected via internet. They communicate to each other with TCP/IP.

The operation system in each computer is different. RT-linux is the real time operation system in Japan side. QNX is the real time operation system in Slovenia side. Programs are executed based on these operation systems. Each program consists of three parts, control thread, communication thread and user process. In RT-Linux, only control thread is executed in RT-kernel as shown in Fig. 4. User process and communication thread is executed in normal linux kernel. Meanwhile, QNX executes every process and threads in RT-kernel as shown in Fig. 5. This structural difference of the operation system doesn't exert any influence on the control system. Communication thread doesn't have to be executed in RT-kernel since it is impossible to achieve real time communication via internet.

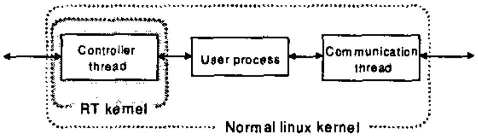

Fig. 4. Architecture of rt-linux

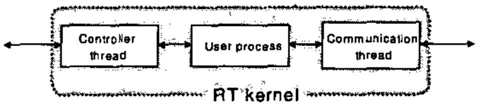

Fig. 5. Architecture of QNX

Real time communication is impossible because time

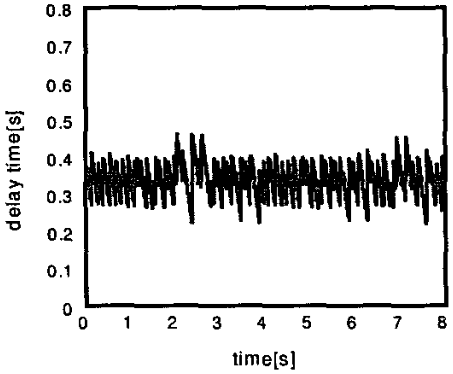

Fig. 6. Communication delay between Slovenia and Japan

variance communication delay occurs in internet communication. One way communication delay between Slovenia and Japan was measured with this system. The result is shown in Fig. 6.

The procedures for master side to measure the time delay is as follows. Slave side can know the round trip time delay similarly.

1) Send the packet from master to slave with the data of master time stamp.
2) Slave receives the packet after a while.
3) Slave sends back the packet with the data of master time stamp immediately.
4) Master receives the packet and compares the current time and the received packet data. The time difference will be round trip time delay.

With these procedures, both master and slave side keep monitoring the communication delay. For simplicity, communication delay $T$ is figured out by dividing the round trip delay to halves.

Communication delay occurs due to various causes such as packet collision, ACK waiting, signal transmission delay, router processing time and PC processing time. Bilateral control system should be constructed considering this time varying communication delay since this degrades the reproducibility of haptic sense and it may even make the system unstable.

## III. Stability Assurance

In this section, we make a brief explanation about the conventional stability assurance method. In the next place, it is shown that there is some unsafe situations even if the control system is perfectly stable.

### A. Wave Variables

We applied wave variable based controller[4], [5] in order to assure the control stability. Velocity and force at master and slave sides are transformed into wave variables, $u_m$ and $v_s$, in this approach.

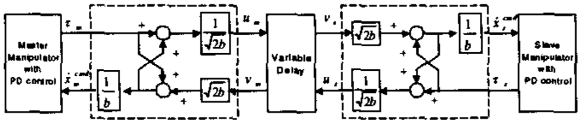

Fig. 7. Wave variable based bilateral controller

Fig. 8. Physical interpretation of wave variable based system

$$u_m(t) = \frac{b\dot{x}_m(t) + \tau_m(t)}{\sqrt{2b}} \tag{1}$$

$$v_s(t) = \frac{b\dot{x}_s(t) + \tau_s(t)}{\sqrt{2b}} \tag{2}$$

where subscript m denotes master side and subscript s denotes slave side. $\dot{x}$ represents velocity of the manipulator. $\tau$ represents a torque exerted to the manipulator. $b$ is an arbitrary positive constant that determines the property of the communication line. $b$ is labeled as "characteristic impedance".

In backgrond materials, $\tau_m(t)$ represents a force exerted to the master arm by the operator, whereas $\tau_s(t)$ means a force applied to the environment by the slave arm. In this paper, both $\tau_m(t)$ and $\tau_s(t)$ represent force exerted to the arm by the operator or the environment. Therefore, the sign of the second term of numerator in (2) is opposite compare to the method in background materials. This comes from the concept that master manipulator and slave manipulator is treated equivalent.

Fig. 7 shows the block diagram of whole system. Two other wave variables at the receiving side, $u_s$ and $v_m$, are defined in the same manner and if the communication line has a constant delay, they are related to $u_m$ and $v_s$ as follows:

$$u_s(t) = \frac{b\dot{x}_s(t) + \tau_s(t)}{\sqrt{2b}} = u_m(t - T_1) \tag{3}$$

$$v_m(t) = \frac{b\dot{x}_m(t) + \tau_m(t)}{\sqrt{2b}} = v_s(t - T_2) \tag{4}$$

where $T_1$ denotes a constant time delay from the master to the slave and $T_2$ denotes the constant time delay in the reverse direction.

The behavior of this system could be interpreted as a distributed mass-spring system. Suppose the communication delay is $T$ in both directions, this system behaves like a spring with stiffness of b/T in static situations, whereas the operator feels virtual viscous force induced by a damper with viscosity of b when the arm is moved in constant speed.

### B. Energy Balance Monitor

Yokokohji et al. [5] extended the concept of wave variable and introduced an energy balance monitor

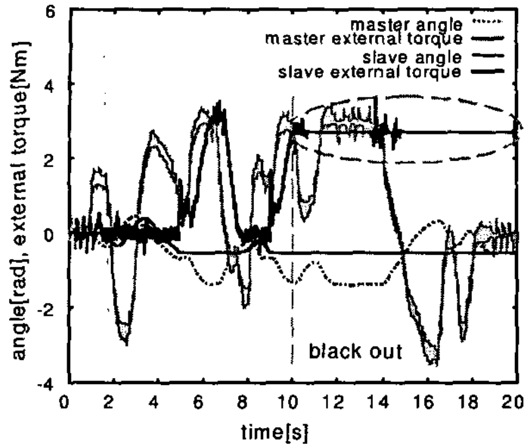

Fig. 9. Conventional method with communication black out

to assure the control stability under time varying communication delay. The condition to continue the operation will be figured as follows.

$$\begin{aligned} E_{total}(t) &= \frac{1}{2}(\int_0^t \|u_m(\varrho)\|^2 d\varrho - \int_0^t \|v_m(\varrho)\|^2 d\varrho \\ &\quad + \int_0^t \|u_s(\varrho)\|^2 d\varrho - \int_0^t \|v_s(\varrho)\|^2 d\varrho) \\ &\geq -E_m^{limit} - E_s^{limit} \qquad (5) \end{aligned}$$

where $E_m^{limit}$ and $E_s^{limit}$ denote appropriate positive constant values in master side and slave side respectively.

### C. Unsafe Situation

There are many conventional studies on stability assurance under communication delay. Some of them also correspond to time variance communication delay including communication blackout. Deceptively, it seems these systems are completely safe. However, there are some unsafe situations in these methods. The example is shown in Fig. 9. Control gains in this experiment are $K_p = 2.4$, $K_v = 0.8$, $K_f = 0.01$. External torque value on slave side is shown reversely in order to compare two absolute values of external torque.

At first in this experiment, 180ms constant time delay was given. Slave manipulator followed behind the motion of master manipulator with human operation. When the slave touched the rigid wall, human operator could feel the reaction force of the wall as if the operator was pushing the wall with the spring. After 10s, virtual communication blackout was realized. Although operation ended with stable control, external force remained on slave side since the slave manipulator was keep pushing the wall. This is because the slave manipulator was pushing the wall and slave manipulator tried to keep the last command. Assume if this was the telesurgery system, the slave manipulator may damage the body of the patient. This shows that local controller is needed in order to keep the safety under time variance communication delay.

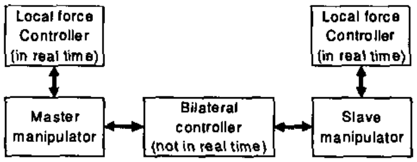

Fig. 10. Basic concept of suggested system

## IV. Control System Considering Safety

### A. Control System with Variable Gain

Global bilateral control system wouldn't work well under large communication delay or communication blackout. In order to keep the safe contact motion of manipulators with objects, control system should pay attention to the changing aspect of contact motion in real time. Therefore it is impossible for the global controller to keep the safe contact motion under communication delay.

Local controller should be mounted to this system and work so that local contact motion will be always in safe. At the same time, global bilateral controller works so that it transmit the haptic sense to the other side. The basic concept is shown in Fig.10.

However, local controller may degrade the performance of the system since it will interfere the input of the global bilateral controller. Consequently, we suggest a method to change over the local controller and global controller gradually depending on communication delay.

If the communication delay becomes large, it is dangerous to keep the constant command value from the global bilateral controller since the command might be changed during the communication delay. For this reason, local controller should be governing the control of manipulator during the large communication delay occurs. On the contrary, the global bilateral controller should be governing when the communication delay is small since the global bilateral controler works well and safe contact motion is achieved by itself.

Applying this method, the safety of bilateral contact motion will be secured even if communication delay becomes large. Furthermore, the performance of the bilateral control would be less degraded since the local controllers are relatively weak when small communication delay exists. The master manipulator control system including the global bilateral controller and the local force controller is shown in Fig. 11. Since bilateral control in this research is symmetrical, the construction of slave manipulator is also the same.

The changeover from global bilateral controller to local controller is done gradually by variable controller gain $K_c$. $K_c$ is figured out as follows.

$$K_c = exp(-\lambda T) \qquad (6)$$

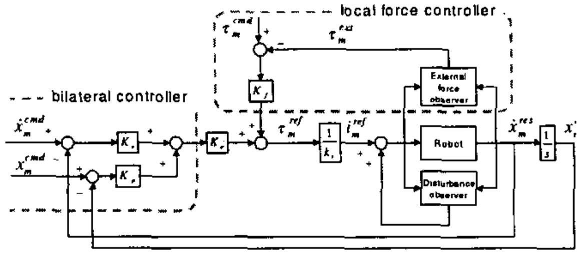

Fig. 11. Control system on master side

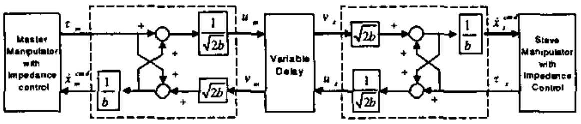

Fig. 12. Suggested bilateral control system

where $\lambda$ is the arbitrary given value that shows the pace of decrease. This is the most simple example and it is possible to set the variable gain in other ways too.

As the communication delay becomes large, the input from global bilateral controller decreases. $K_f$, the force feedback gain of the local controller, will be set relatively small so that the local controller will less degrade the performance. $\tau_m^{cmd}$ is the command input of the local controller. It is decided due to the situation. If the operation is to press the obstacle, it is able to secure the safety setting $\tau_m^{cmd}$ to 0. If the operation for the slave manipulator is to carry the obstacle, to keep holding the obstacle stands for safety. Therefore, $\tau_m^{cmd}$ should be figured out from the grip force. It is also possible to plan $\tau_m^{cmd}$ by some intelligent control system.

### B. Applying Stability Assurance Method

Although it is important to mount local controller, the existence of local controller may make the stability assurance method complex. In order to avoid this, the whole control system is treated as a global bilateral control system with impedance controller on master and slave side as shown in Fig. 12. Since impedance controller realizes mechanical impedance motion, it is also able to interpret the system as mass-spring system. The conventional stability assurance method could be applied easily. This interpretation is only for stability assurance. Hence, the local controllers are individually designed. Wave variable concept itself does not assure the stability if the control gain varies in conjunction with the communication delay. With energy balance monitor, it is able to assure the stability.

### C. Experiment Through Internet

Teleoperation experiment between Slovenia and Japan was done in order to validate the method by the system with actual communication delay. Fig. 13 shows the Video image of the experiment. Control gains in Japan side are equivalent to the experiment in section III-C and $\lambda$ is 0.42. Control gains in Slovenia side are $K_p = 0.06$, $K_v = 0.02$, $K_f = 0.002$, External torque value on slave side is shown reversely in order to compare two absolute values of external torque.

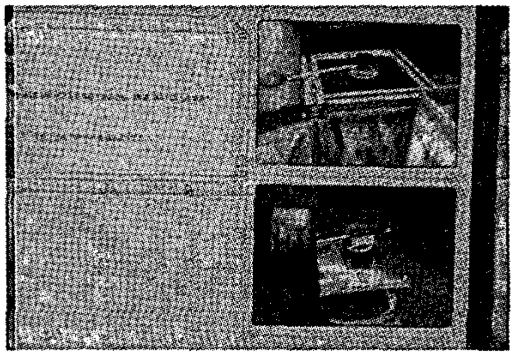

Fig. 13. Video image of experiment

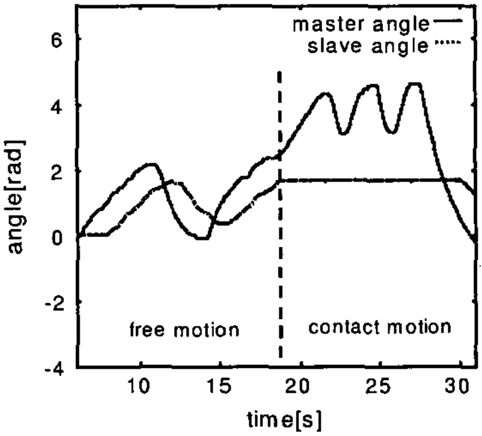

Fig. 14. Teleoperation experiment between Slovenia and Japan(angle response)

It was able to feel the haptic sense of pushing wall in the distant place, with the communication under large variance delay. Fig. 14 and Fig. 15 shows the result of the experiment. The external torque value shows both, the force from the wall in slave side and the force due to the operating force of human. Since virtual mass and virtual friction of the manipulator becomes large as the communication delay becomes large, operational force becomes large compare to the transmitted force. This kind of degradation is a common problem of bilateral system under communication delay.

### D. Experiment with Communication Blackout

Virtual communication blackout was given during the operation. Fig. 16 shows the result. Control gains are completely equivalent to the experiment in section III-C and $\lambda$ is 0.42. External torque value on slave side is shown reversely in order to compare two absolute values of external torque. Soon after the communication blackout, changeover from global bilateral controller to

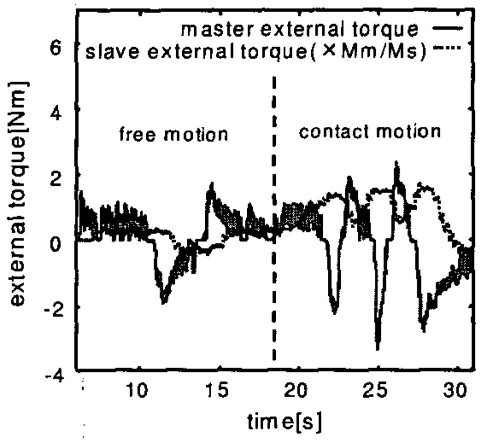

Fig. 15. Teleoperation experiment between Slovenia and Japan(torque response)

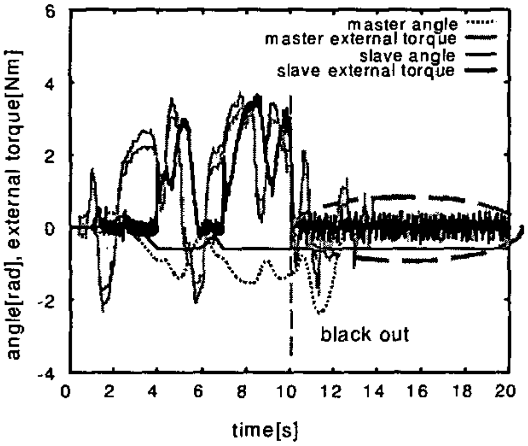

Fig. 16. Experiment with suggested controller

local controller was carried out. Therefore, the external torque value soon converged to 0. Safe operation was achieved with this suggested controller.

## V. Conclusion

Safety of bilateral control under time variance communication delay was discussed in this paper. It is shown that the control stability assurance in bilateral control under time variance communication delay does not always stand for operation safety. Local controller is needed to secure the safety when communication delay becomes large. A novel method to change over the local controller and global bilateral controller due to communication delay is suggested. At the same time, the stability of global bilateral control is also assured with the conventional stability assurance method. Experimental system that joints manipulators in Slovenia and Japan is constructed. The validity of the suggested method is shown with this experimental system. To evaluate the safety of these systems quantitatively should be the future works since it is a very important issue for practical systems.

## ACKNOWLEDGEMENTS

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